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RESEARCH ON DISTRIBUTED FERRITES FOR CROSSED-FIELD MICROWAVE DEVICES

QUARTERLY REPORT

by

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RESEARCH ON DISTRIBUTED FERRITES

FOR

CROSSED-FIELD MICROWAVE DEVICES

4th Quarterly Report

10 November 1966 - 9 February 1967

Report No. 4

Contract No. DA28-043-AMC-02032(E)

Prepared by

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For

U. S. Army Electronics Command
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ABSTRACT

The objective of this program is to develop the knowledge and technology necessary to take full advantage of the unidirectional attenuative properties of ferrites in achieving improved gain and bandwidth in crossed-field microwave amplifiers and oscillators.

During this fourth quarterly period, activities included further cold testing of ferrite materials in the L-band cold test vehicle and in the S-band QKS1267 Amplitron. A number of brazing experiments were carried out, and considerable effort was expended in the study of hot pressing techniques for the bonding of ferrites to alumina. The results were promising.

The results of both theoretical and experimental studies of broadbanding have been encouraging. In particular, desirable properties have been demonstrated over half an octave in S-band with a porous manganese ferrite.

The results of the first year's work suggest that good rf performance is fairly easy to achieve but that the demonstration of these properties in an actual CFA must await solution of the technological problems of bonding and exposure of the ferrites to tube brazing conditions. The major aim of the second year will be the realization of hot tests at the earliest possible time.

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1. PURPOSE

The objective of this program is to develop the knowledge and technology needed to take full advantage of the unidirectional attenuative properties of ferrites in achieving improved gain and bandwidth in crossed-field microwave amplifiers and oscillators. This objective will be achieved by reducing circuit feedback and reflections with minimum insertion loss through the use of ferromagnetic materials. Improvement of compactness and weight will also result from the utilization of ferromagnetic materials in crossed-field devices.

2. SCOPE

The program shall consist of a theoretical and experimental study of various problem areas. The emphasis in this program will be on the interaction of ferrites with broadband delay lines suitable for crossed-field devices. The experimental work may be conducted at any convenient microwave frequency. However, both the experimental and theoretical information must be such that it can be utilized at all microwave frequencies up to 10 GHz. The particular tasks to be undertaken will ba as outlined in U. S. Army Electronics Command Guideline No. MW-47, dated 2 September 1965.

3. INTRODUCTION

This fourth quarterly report marks the mid-point of a year program directed toward the inclusion of ferrite devices in crossed-field tubes. Consequently, it is considered worthwhile to present a brief review of the principal accomplishments thus far. These follow:

a. The establishment of a simple design theory for distributed ferrite isolation in CFA structures.

b. Considerable cold testing of L-band helix and meander structures with R-142 ferrite, verifying design theory, demonstrating relative ease of obtaining suitable ferrite isolator properties, with principal rf limitations in bandwidth and fast mode propagation.

c. The study of special ferrite application for frequency selective damping of Amplitron oscillations.

d. An extensive survey of existing ferrite materials for potential CFA application from L band to X band, and establishment of design rules in choosing suitable combinations of demagnetization, shape, linewidth, and high temperature properties.

e. Studies of bonding with generally negative decisions of glass frit and thin film bonding of ferrite to ceramic, ceramic box techniques (at least for circular format), and direct metal to ferrite bonds. Successful tests with hot-pressing technique has led to a decision to rely on this technique for putting ferrites into the hot tube test vehicle.

f. Brazing tests with a few ferrites under vacuum, inert, and reducing atmosphere have suggested possible serious problems with ferrite decomposition under usual tube brazing conditions.

The results of the first year suggest that good rf performance is fairly easy to achieve and the design problems are not serious though significant. The technological problems of bonding and exposure to tube brazing conditions are much more serious. Since a solution of the latter is required before the promising rf properties can be demonstrated in an actual CFA, it is clear what the philosophy should be for the second year. The priority items on the list of pending or possible tasks are those involved in enabling the successful realization of some hot tests as early as possible, preferably with an optimum porous ferrite for wide bandwidth but at least with any ferrite as long as it gets into a tube.

Thus, in order of priority, the following areas of investigation will be pursued during the second year.

a. Further development of hot pressing technique with objective of early delivery of a ferrite-ceramic assembly for use in cold tests and then in hot tubes.

b. Early tests on ferrite decomposition under brazing atmospheres. Selection of a compatible combination of ferrite material and tube brazing conditions. Hopefully this will be a porous ferrite because of its wide bandwidth potential.

c. Incorporation of ferrites into hot test vehicles preceded by cold tests on porous ferrites in linear and circular S-band structures.

d. Experimentation with hot test vehicle under low duty cycle, first to determine influence of ferrite on bandwidth, gain and stability and nature of remaining oscillations, if any. After sufficient results of this kind are obtained, the thermal problems will be explored by CW operation.

Along with these necessary tasks other things will be done if time and priority permit:

e. Study of the thermal design problem and influence on selection of ferrite material and location of ferrite in tube.

f. Further study of electromagnetic behavior including dielectric loading, influence on slow wave dispersion, design techniques for large bandwidth such as "stagger tuning" properties of porous ferrites, and interaction with fast modes.

g. Review of design considerations from L band to X band and study of alternate ways of using ferrites in achieving CFA stability - i. e., delineating the different types of CFA oscillation problems and tailoring ferrite techniques for each case.

During the fourth quarterly period, activities included further cold testing of ferrite materials in the L-band cold test vehicle and in the S-band QKS1267 Amplitron. A number of brazing experiments were carried out and considerable effort was expended in the study of hot pressing techniques for bonding of ferrites to alumina. The results of this effort will be found in subsequent sections.

4. COLD TEST PROGRAM

During this report period, the studies of the ferrite-loaded L-band helix were continued. Further investigation of the use of narrow line-width ferrites to suppress band-edge oscillations in an S-band Amplitron was made.

Figure 4-1 illustrates the geometry of the helix delay line which was employed in the cold test experiments. A twelve-inch slab of ferrite was inserted into the helix delay line with the axis of the sample oriented in the direction of wave propagation. For L-band tests, a Raytheon nickel-aluminum ferrite, no. R142, and a Sperry ferrite, M-40, were examined. The essential characteristics of these two materials are listed in Table 4-1.

Table 4.1. Essential Characteristics of Ferrite Materials

Parameter	R-142	M-40
$4\pi M_s$	450 gauss	800 gauss
ΔH	300 oersteds	600 oersteds
γ		3.89
T_c		370°C
$\tan\delta$		0.002

In the case of the R-142, the computed value of the ferromagnetic resonance field at 1.5 GHz was 460 oersteds for a cross-section of $l = 0.40$ inch and thickness $\Delta X = 0.090$ inch. The magnetic field is considered to be in the l direction. For the sample of M-40 material having the same physical dimensions of the R-142, the resonant magnetic field was 327 oersteds at 1.5 GHz.

The demagnetization factors employed in the computation were:

$$N_x = \frac{l}{l + \Delta X} \qquad N_z = 0 \qquad N_y = \frac{\Delta X}{l + \Delta X} \tag{4-1}$$

The computed backward-wave attenuation was obtained from the following relationship,

$$\text{Helix attenuation } \alpha(\text{db/cm}) = 0.230\,(\Delta X)\,(\sinh \frac{3.5\,X_o}{W}), \tag{4-2}$$

where ΔX is in centimeters.

For the S-band tests, ferrites were placed over the strapped-vane delay line of the QKS1267 S-band Amplitron as illustrated in Figure 4.2. This Amplitron is rated at 60 kW peak power, 3% duty cycle, and 16 db gain in the band 2.9 to 3.1 GHz. The tube has undesired band-edge oscillations. These voltage tunable oscillations appear as the pulse voltage rises through the synchronous voltage range. The oscillations are sustained by regenerative circuit and electronic feedback through the tube's drift region. The purpose of the ferrite is to introduce a high bilateral loss at the band-edge frequencies while presenting low losses in the operating band of the Amplitron.

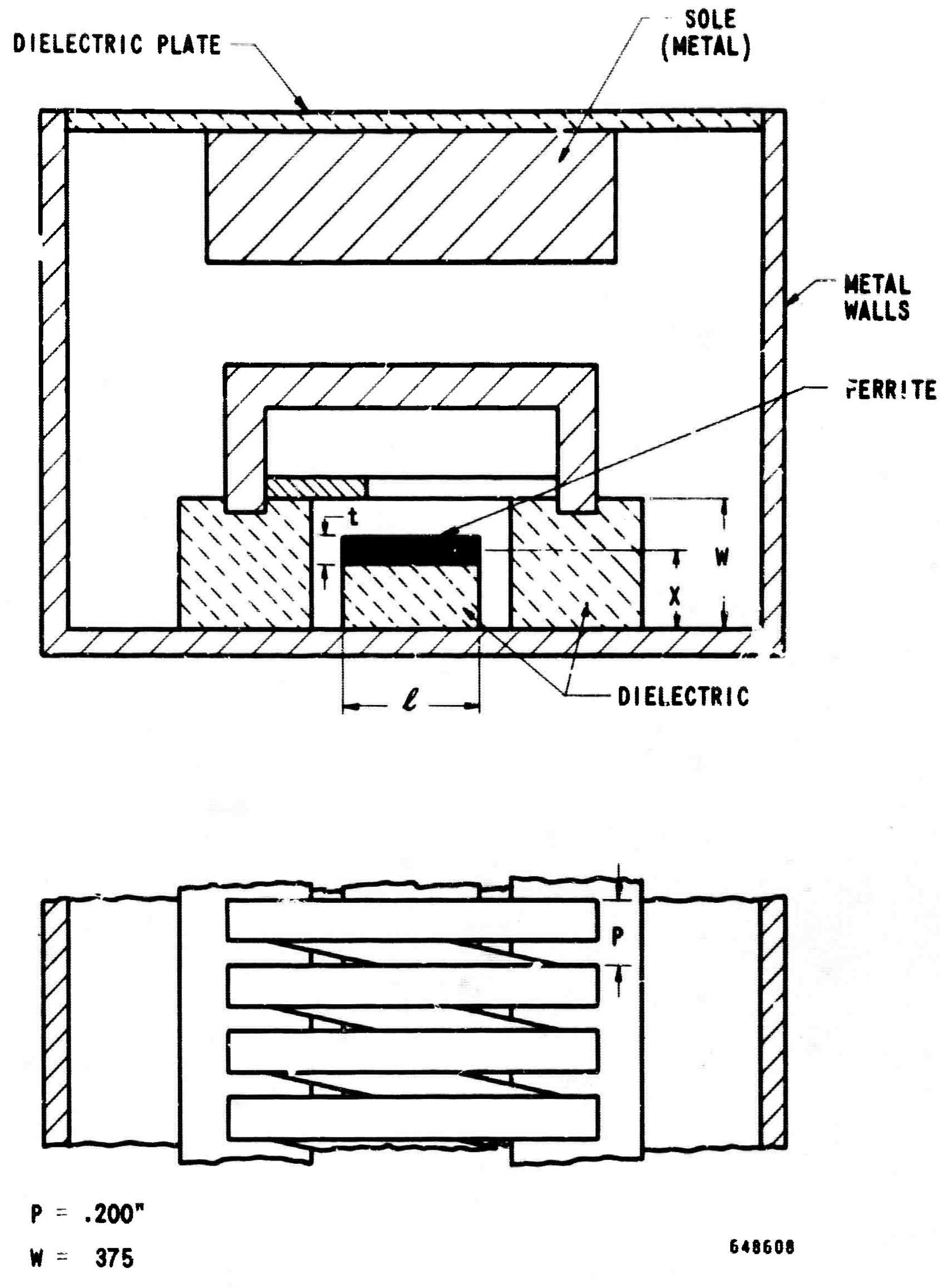


Figure 4-1 Helix Delay Line Cross-Sectional View

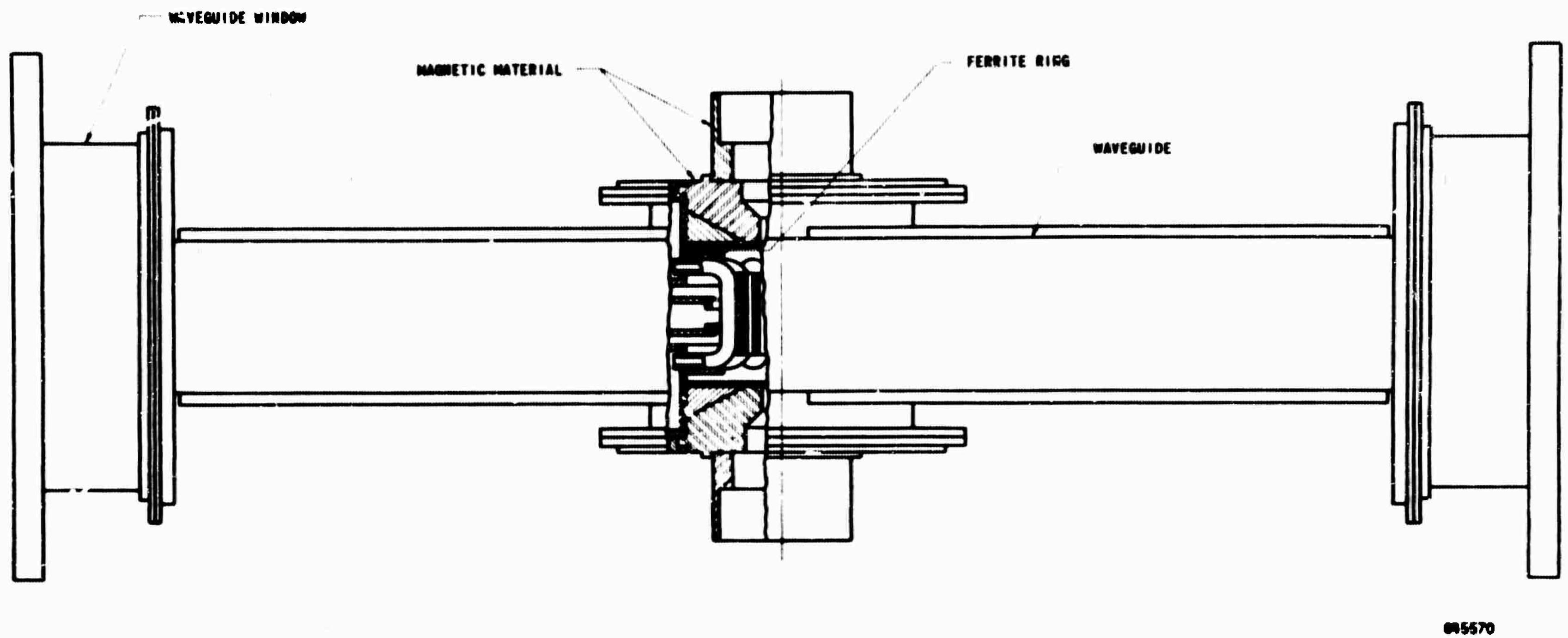


Figure 4-2 QKS1267 Delay Line Assembly (With Ferrite Ring)

Cold tests were carried out in the following areas:

1. Study of the effect of wider linewidth ferrite material, ΔH, on overall bandwidth.

2. Continuation of the tests of ferrites mounted on a metal base.

3. Examination of the effect of ferrite on fast mode propagation.

4. Continuation of the effort to develop a narrow linewidth ferrite which will attenuate band-edge oscillations in Amplitrons.

As in prior cold test work, the measurements were made with a conventional reflectometer set-up. The losses were determined from comparison of transmission data of the loaded and unloaded lines. The cold test measurements were taken on the cold test model developed in the previous quarter and having an improved coaxial-line-to-helix match.

Cold test results. In the third quarterly report, the result of mounting the ferrite directly on a metal base instead of on the usual dielectric support was discussed. Cold test investigation in this area was justified by the less severe problem associated with a metal-to-ferrite bond in contrast to a ferrite-dielectric bond. As anticipated, the data indicated that when the ferrite is mounted on a metal base the metal support distorts the circularly polarized rf magnetic field. In past experiments, the ferrites have been cemented to the metal base with an organic glue. Thus it was highly probable that an air interface existed between the ferrite and the metal. The experiments were repeated by bonding the ferrites to the metal base with indium solder. This metallic solder eliminated any possibility of an air interface. The observed backward-wave power losses data are given in Figure 4-3 for various X/W ratios, while Figure 4-4 shows the corresponding forward-wave loss for X/W = 0.653. Since results with the indium soldered ferrite samples were not significantly different from previous data, it was concluded that any small air space between the ferrite and metal base had little influence on the cold test measurements.

To obtain a wider band ferrite loss, a ferrite material, M-40, possessing a wider magnetic resonance, $\Delta H = 600$ oersteds, was selected for test.

The observed backward and forward-wave losses are plotted in Figure 4-5. Both forward and backward-wave power losses showed an increase with frequency. Only a small indication of a resonance was observed.

Other values of dc magnetic field produced the same general results. After the completion of these tests, the Special Microwave Devices Operation of Raytheon examined the characteristic of this ferrite. In these tests, sample pieces were placed in the rf fields of a waveguide and evaluated. The results were similar to our test data on the helix. The observed discrepancy of results for the M-40 ferrite is presently under study.

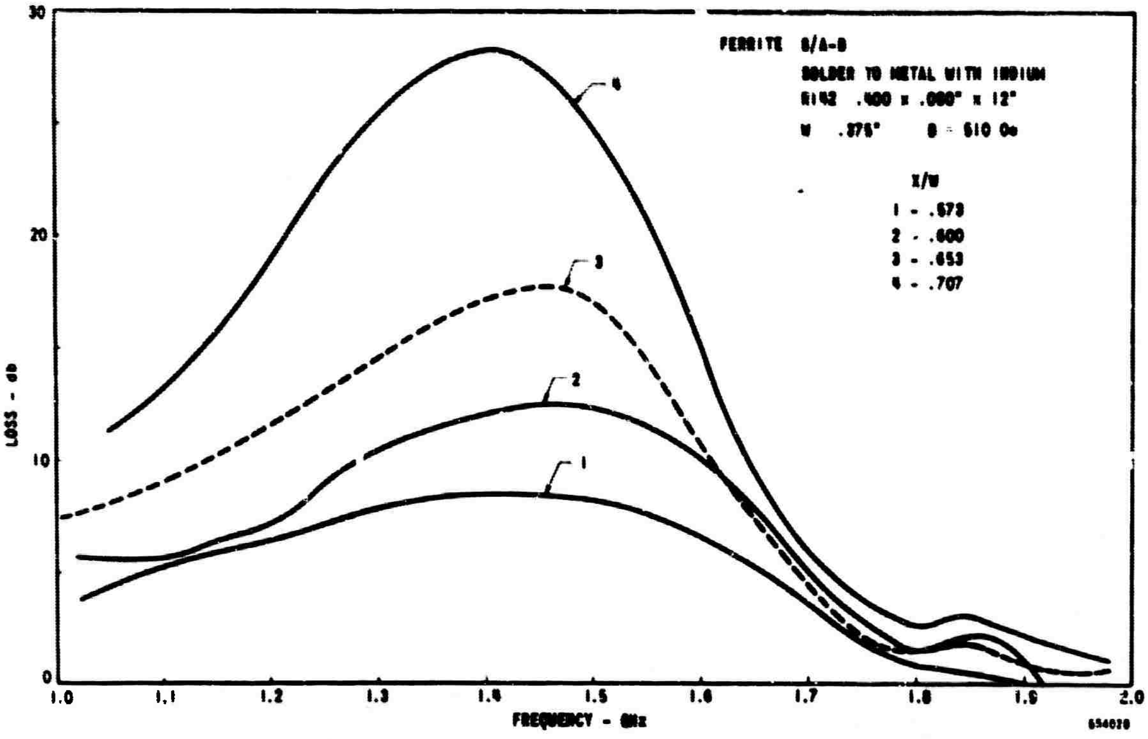


Figure 4-3 Helix - Backward-Wave Power Loss - db

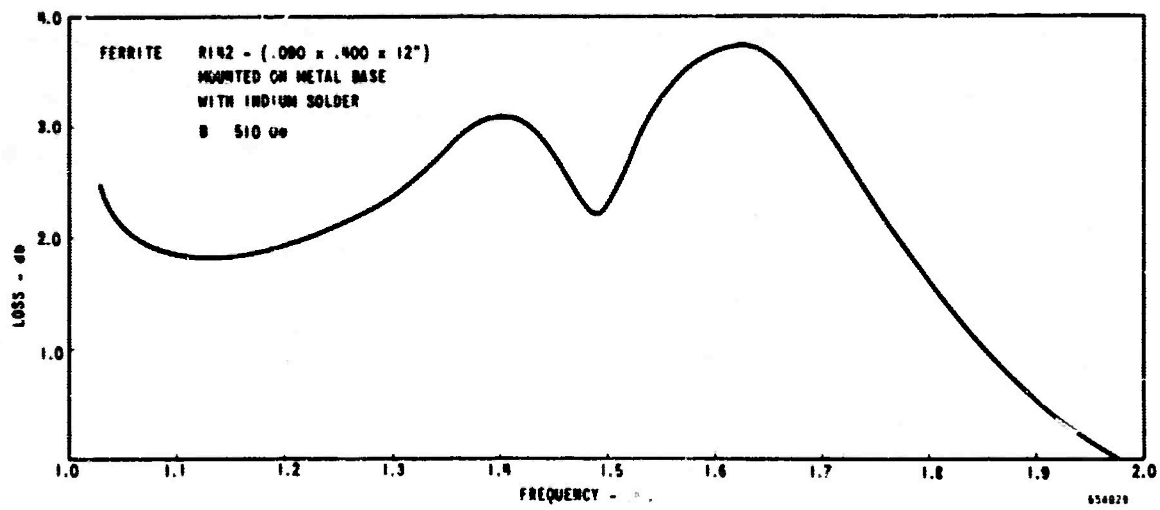


Figure 4-4 Forward-Wave Power Loss - db - Helix

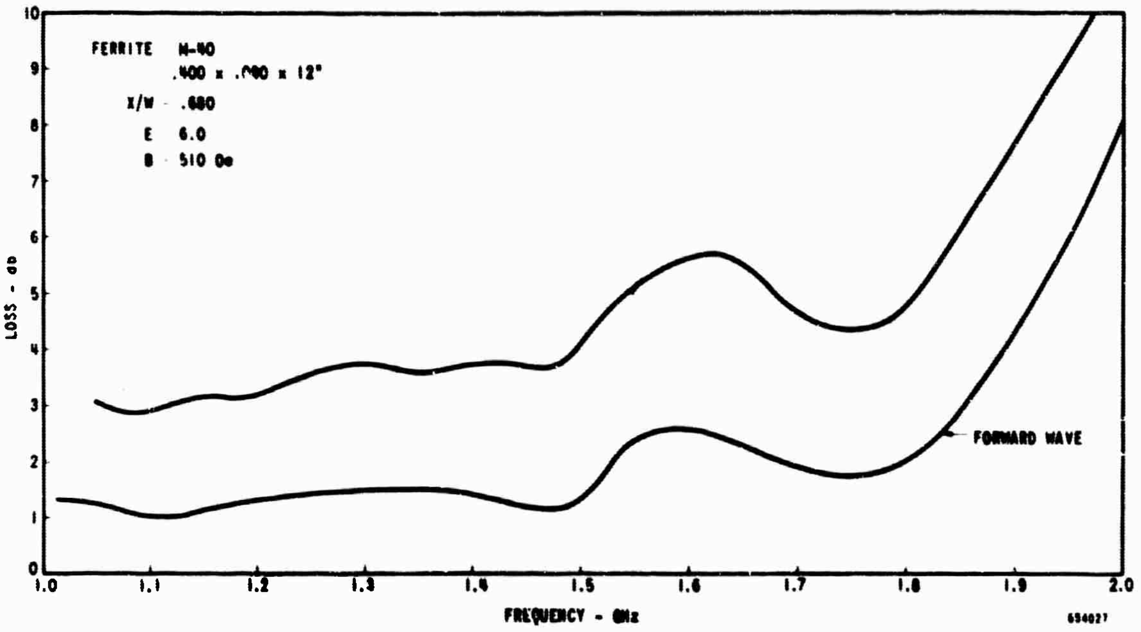


Figure 4-5 Backward and Forward Wave Power Losses Helix Delay Line

In crossed-field devices, cyclotron-wave interaction with fast modes or fast mode feedback into the circuit input or gun region can be a serious problem. The isolated sole of these devices enhances propagation of fast modes. To study these modes, a four-port network was constructed as shown in Figure 4-6. To obtain valid measurements, it was necessary to shield the entire structure to prevent radiation of the fast modes. As stated in the third quarterly report, the magnetic field had little effect on suppressing the fast modes when ferrites were located in the normal position. These results were anticipated. Since the sole is a very active element in the propagation of fast modes, a ferrite located in the vicinity of the sole should be effective in suppressing the fast modes. To confirm this reasoning, a damping material was placed between the sole and a metal conductor. All modes propagated from port 2 to port 4 were highly attenuated. Thus, it appears that the ferrite can be useful in suppressing fast modes if deployed in a specialized location.

In the third quarterly report, the band edge oscillation phenomenon was discussed as it pertained to the QKS1267 S-band pulsed Amplitron. As mentioned, cold test work was directed towards the possibility of highly selective damping of the lower band-edge frequencies. It was desired that the ferrite loss peak at 2850 MHz, the point of 50% input reflection coefficient, when a field of 2400 gauss was applied. In the first attempt, a Raytheon R-171 material ($4\pi M_s = 1750$) was investigated. The samples were ground into thin discs. The dc magnetic field necessary for ferromagnetic resonance was found to be well below the normal tube magnetic field. Although thinner discs and changes in pole geometry brought the two field values closer, their difference was still too great. In this quarter, it was attempted to increase the ferromagnetic resonant dc magnetic field through the selection of a material with a higher $4\pi M_s$. Discs of Raytheon R-161 were tested. The ferrite had the following properties:

$4\pi M_s$	3120
ΔH	173 oersteds
γ	3.26

The following disc shapes were examined:

1.700 in. ID x 0.900 in. OD x 0.025 in.
1.700 in. ID x 0.090 in. OD x 0.030 in.
1.600 in. ID x 0.090 in. OD x 0.025 in.
1.600 in. ID x 0.900 in. OD x 0.025 in.

The results were similar for both types of ferrite material. There was no appreciable increase in dc magnetic field for ferromagnetic resonances. At the present time, the results are not explainable in depth but are believed to be associated with the non-uniform magnetic fields which unavoidably exist in the vicinity of the ferrite discs.

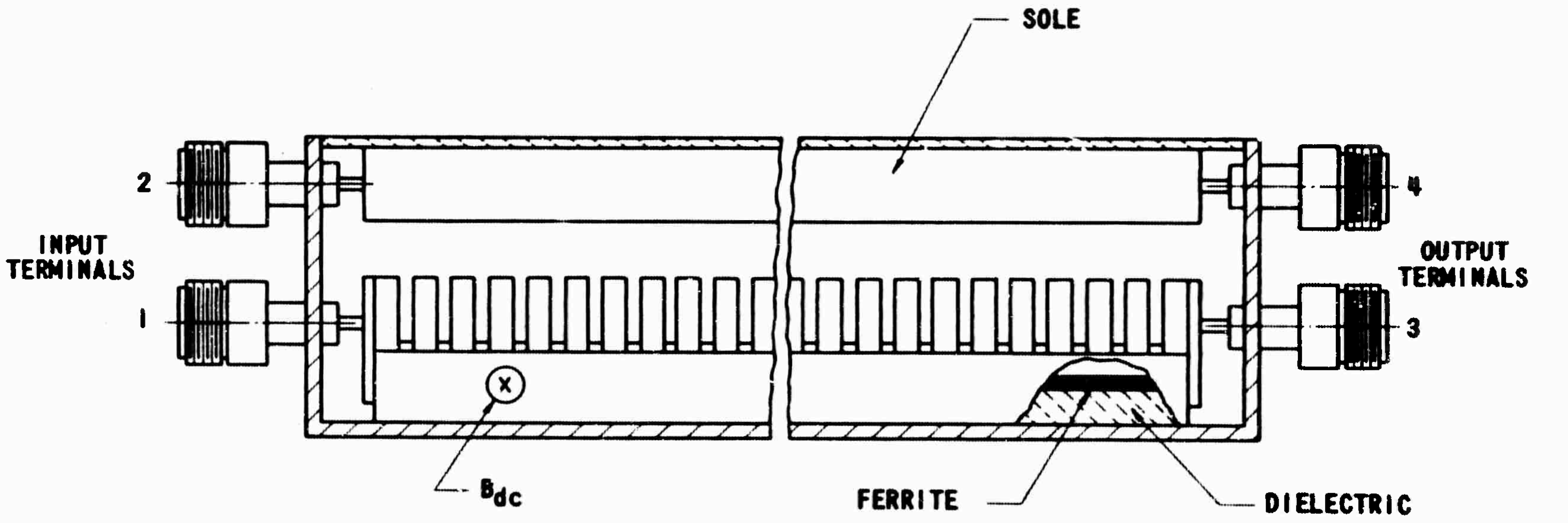


FIGURE 4-6 Helix Delay Line - 4 Terminals
Cross - Sectional View

5. FERRITE BRAZING AND FIRING

Several porous ferrites were brazed to metal (at 800 - 850°C) under various atmospheres - vacuum, inert gas, and a reducing atmosphere. In all cases, the ferrite properties were drastically degraded. This was surprising since there have been reports of moderately successful brazes with only slight changes in ferrite properties. It suggests that possibly the firing of porous ferrites in the absence of oxygen may destroy the ferrite, whereas a dense ferrite may survive. Consequently, work on ferrite-to-metal brazes will be halted, and firing tests on the ferrites will be made. To effect the best possible useage of talents, the following arrangements have been set up among SMDO (Special Microwave Devices Operation), the Research Division and Microwave and Power Tube Division.

1. SMDO will be responsible for running the experiment. SMDO will procure the necessary samples, organize and expedite all aspects of their measurement and baking, and collect, record and report the test data.

2. The samples will be baked at 400°C, 600°C and 800°C in vacuum and argon. The 400°C is typical for tube bakeout, and the higher temperatures are representative of possible tube brazing temperatures.

3. The bake cycles, which are related to actual tube processing, will be as follows:

    a. A 400°C vacuum - eight hours - bakeout condition.

    b. All other temperatures, vacuum and argon - 30 minutes at temperature. Heating and cooling times to be similar to those expected in tube brazing operations.

4. Five materials have been selected as follows:

    a. Raytheon (SMDO) R-161 Dense Ni Ferrite.

    b. Raytheon (SMDO) R-164 Porous Ni Ferrite.

    c. Raytheon (SMDO) R-151 Dense MgMn Ferrite.

    d. Raytheon (Research Division) MF-10187-22-B-48-284 (10273) Porous MgMn Ferrite.

    e. TransTech G-1003 Dense YGd Garnet.

    These selections have been made to compare three basic classes of materials and also, within a given class, to establish whether porosity has any bearing on decomposition.

5. For each material, there will be eight pairs of samples, each pair consisting of a 0.060 inch diameter sphere and a 0.040 inch diameter by 5/8 inch rod. The eight pairs will be used as follows:

Sample No.	1	2	3	4	5	6	7	8
Purpose	400°C Vac.	600°C Vac.	800°C Vac.	400°C Argon	600°C Argon	800°C Argon	Control	Spare

For the five materials involved, this implies that forty spheres and forty rods or a total of eighty samples are required.

6. The measurements to be made before and after baking are as follows:

   a. Spheres - $4\pi M_s$ and ΔH in X-band.

   b. Rods - tan δ in X-band and μ'' in C-band.

7. The outline procedure is as follows:

   a. Cut sample blanks (SMDO)

   b. Grind spheres and rods (Research Division)

   c. Measure all samples (Research Division)

   d. Bake cycles (Power Tube)

   e. Remeasure after bake (Research Division)

8. The program schedule, requires that the experiment be completed by March 17, 1967.

6. BROADBANDING TECHNIQUES

One of the objectives of this contract is to build a resonant ferrite device having a back-to-front ratio and insertion loss compatible with the good operation of the crossed-field amplifier tube. It must cover the same frequency range as the tube, ie, up to an octave.

Such broadband performance can be attained by several means:

a. Using a single resonance device with broad line-width materials.

b. Using multiple resonance, by varying applied field, material properties, demagnetization factors or a combination of each.

6.1 Single resonance device. In previous reports, it has been shown that the bandwidth of a ferrite device having a single resonance is related to the material properties through the expression

$$\Delta\omega = \gamma \Delta H \tag{6-1}$$

where $\Delta\omega$ is the bandwidth at half power
γ is the gyromagnetic ratio of the material
ΔH is the linewidth of the material.

In consequence, if a broad frequency range of operation is to be improved, a broad linewidth material is necessary. This particular material property can be obtained by several means.

6.1.1 Linewidth broadening by substitution. The ferrite material properties can be altered and adjusted between certain limits by addition or substitution of elements in the basic composition.

Such ferrites as Sperry no. 40 (Ni, Cu, Co, Mu, Al, Fe) with ΔH = 600 oe, and Transtech TT2-118 (Ni, Co, Al, Fe) with ΔH = 800 oe, are typical of this class of materials.

The loss in a resonant ferrite device can be represented by the dissipative part of the susceptibility. For a material responding to circularly polarized microwave magnetic fields, it can be written:

$$\mu''_{\pm} = \frac{\omega_M T}{(\omega_o \mp \omega)^2 T^2 + 1} \tag{6-2}$$

where ω_o = γ Ho the resonant frequency given by Kittel's equation
ω_M = $\gamma\, 4\pi M_S$ with M_S = the saturation magnetization
ω = the frequency of operation
$T = \frac{2}{\gamma \Delta H}$ = the relaxation time of the ferrite material.

At resonance $\omega = \omega_o$, equation (6-2) becomes:

$$\mu''_{+} = \omega_M T \quad \mu''_{-} = \frac{\omega_M T}{(2\,\omega_o)^2 T^2 + 1}, \tag{6-3}$$

so the maximum theoretical back-to-front ratio will be given by:

$$R = \frac{\mu''_{+}}{\mu''_{-}} = (2\,\omega_o)^2 T^2 + 1, \tag{6-4}$$

and, since in most cases $(2\omega_o)^2 T^2 >> 1$, one obtains

$$R = (2\,\omega_o)^2 T^2 = \left(\frac{4\omega_o}{\gamma\Delta H}\right)^2 \qquad (6\text{-}5)$$

It can be seen that the back-to-front ratio will decrease when ΔH increases. From equation (6-3) one gets

$$\mu''_+ = 2.\,\frac{4\pi M_s}{\Delta H} \qquad\qquad \mu''_- \cong \frac{1}{8}\,\gamma^2\,\frac{4\pi M_s}{\omega_o^2}\cdot\Delta H \qquad (6\text{-}6)$$

The isolation represented by μ''_+ will decrease with increasing ΔH; while, in the same conditions, the insertion loss (μ''_-) will increase.

It will be shown to be true when experimental result are given later in the report.

6.1.2 Linewidth broadening by porosity adjustment. If a ferrite material is made porous by proper preparation, each grain of basic material can be considered as a single resonator, and, with grains of varying sizes and varying demagnetizing factors, an apparent broad banding of the material occurs.

Consider, for simplification, a material where two grain sizes resonate at ω_o and $(\omega_o + \delta)$ where is small. The grains occupy two equal parts of the total volume of material, ie, $V_1 = V_2 = V/2$. The expression (6-2) becomes:

$$\mu''_+ = \frac{V_1}{V}\,\frac{\omega_M T}{(\omega_o - \omega)^2 T^2 + 1} + \frac{V_2}{V}\,\frac{\omega_M T}{(\omega_o + \delta - \omega)^2 T^2 + 1} \qquad (6\text{-}7)$$

$$\mu''_- = \frac{V_1}{V}\,\frac{\omega_M T}{(\omega_o + \omega)^2 T^2 + 1} + \frac{V_2}{V}\,\frac{\omega_M T}{(\omega_o + \delta + \omega)^2 T^2 + 1} \qquad (6\text{-}8)$$

Equation (6-6) reaches a maximum for two values of ω,

$$\omega = \omega_o \qquad (6\text{-}9)$$

$$\omega = \omega_o + \delta \qquad (6\text{-}10)$$

and in each case (6-6) becomes:

$$\mu''_+ = \frac{1}{2}\,\omega_M T\left[1 + \frac{1}{\delta^2 T^2 + 1}\right] \qquad (6\text{-}11)$$

...us, the isolation curve is broadened, since there are two peaks separa... by δ. At the same time the isolation is decreased by a ratio

$$\frac{\mu''_{+\,porous}}{\mu''_{+}} = \frac{1}{2}\left[1 + \frac{1}{\delta^2 T^2 + 1}\right] \qquad (6\text{-}12)$$

if δ is kept small this ratio is close to 1. At the same time, equation (6-7) becomes

$$\mu''_{-} = \frac{\omega_M T}{(\omega_o + \omega)^2 T^2 + 1}\,\frac{1}{2}\left[1 + \frac{(\omega_o + \omega)^2 T^2 + 1}{(\omega_o + \delta + \omega)^2 T^2 + 1}\right] \qquad (6\text{-}13)$$

Since the assumption that $(\omega_o + \omega)^2 T^2 >> 1$ is still valid, one gets at resonance: for $\omega = \omega_o$ and $\delta << 2\omega_o$

$$\mu''_{-} = \frac{\omega_M}{(2\,\omega_o)^2\,T} \approx \frac{\gamma^2\, 4\pi M_s\,\Delta H}{8\,\omega_o^{\,2}} \qquad (6\text{-}14)$$

The insertion loss is pr... ...onal to the linewidth of the grain material.

The back-to-front ratio in this case becomes:

$$R = \frac{\mu''_{+}}{\mu''_{-}} = 8\left(\frac{\omega_o}{\gamma\Delta H}\right)^2 \left[1 + \frac{1}{\delta^2 T^2 + 1}\right], \qquad (6\text{-}15)$$

which is practically equal to the ratio which would be obtained with the narrow linewidth material if δ is kept small ($\delta^2 T^2 << 1$).

In conclusion, by using a ferrite material having an intrinsic narrow linewidth, the resonance bandwidth can be increased by making the material porous at the cost of a decrease in isolation given by (6-12)

Later in the report an example of such a material made at Raytheon Research Division will be given.

6.2 Multiple resonance device. To broadband a resonant ferrite isolator, we can built it as a succession of devices each resonating at a different frequency.

The resonant frequency of a slab of ferrite material is given by Kittel's equation:

$$\omega_o = \delta \left\{ \left[H_a + (N_x - N_y)\, 4\pi M_s \right] \left[H_a + (N_z - N_y)\, 4\pi M_s \right] \right\}^{1/2} \qquad (6\text{-}16)$$

where H_a = the applied field, and

N_x, N_y, N_z are the demagnetization factors dependent upon the specimen shape.

Consequently, to vary the resonant frequency, three means are available to us:

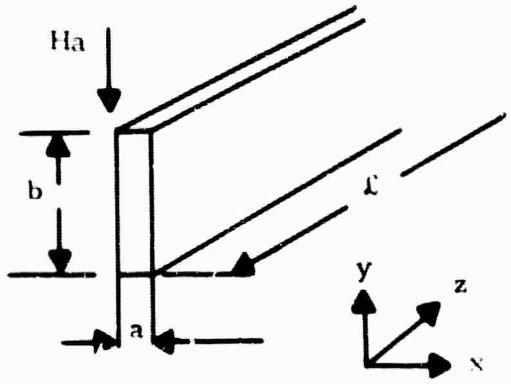
a. The applied magnetic field can be varied by using different magnets or tapering a gap, for instance. But, in our particular application, the applied magnetic field is the same one as the tube's, so the choice of value has to be comparable with the CFA's requirements.

b. The saturation magnetization. Keeping the applied magnetic field constant and identical shape of slab, broadbanding can be achieved by chosing two or more different materials. Some limitation is given to this method by the fact that only certain ranges of saturation magnetizations are available.

c. The demagnetization factors. With the applied magnetic field held constant and using a single material, the resonant frequency of the device can be changed by changing the slab configuration. Again, there are definite limitations to the method.

To help the design of such a composite isolator, curves were drawn which give the ferrite slab shape as a function of frequency with $4\pi M_s$ as a parameter. The curves were traced for different applied magnetic fields.

It has been assumed that the ferrite slabs are always long compared to the other dimensions: in this case, the following approximations can be taken:



$$\mathcal{L} >> b,\ a$$

$$N_x = \frac{b}{a+b} \quad N_y = \frac{a}{a+b} \quad N_z = 0$$

Therefore, Kittel's equation (6-16) can be rewritten

$$\left(\frac{b}{a}\right)^2 \left[\left(\frac{\omega_o}{\gamma}\right)^2 - Ha\,(Ha + 4\pi M_s)\right] + \left(\frac{b}{a}\right)\left[2\left[\left(\frac{\omega_o}{\gamma}\right)^2 - Ha^2\right] + 4\pi M_s\,(Ha + 4\pi M_s)\right] + \left(\frac{\omega_o}{\gamma}\right)^2 - (Ha - 4\pi M_s)^2 = 0 \qquad (6\text{-}17)$$

The solutions of this equation for L-band (1.0 to 2.0 GHz) are shown in Figures 6-1 and 6-2 where

$600 < 4\pi M_s < 1200$ g

Ha = 450 g, 590 g

γ = 3.6

The solutions for S-band (2.0 to 4.0 GHz) with

1000 g $< 4\pi M_s <$ 3000 g

Ha = 850 g, 1070 g

γ = 3.6

are shown in Figure 6-3 and 6-4. With these curves, one can choose material and slab shape for resonance at a given frequency and applied magnetic field.

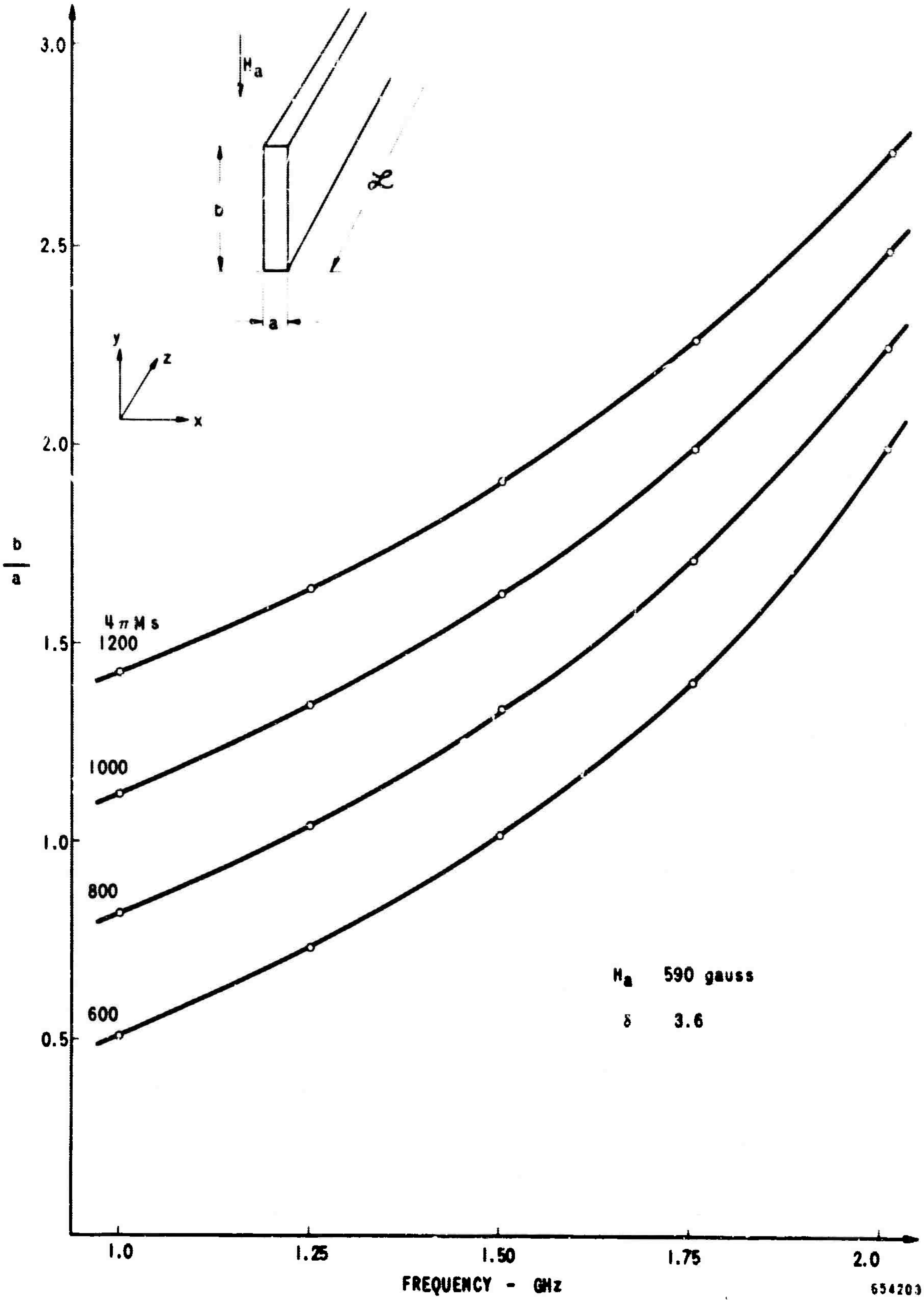


Figure 6-1 b/a vs Frequency - L-Band

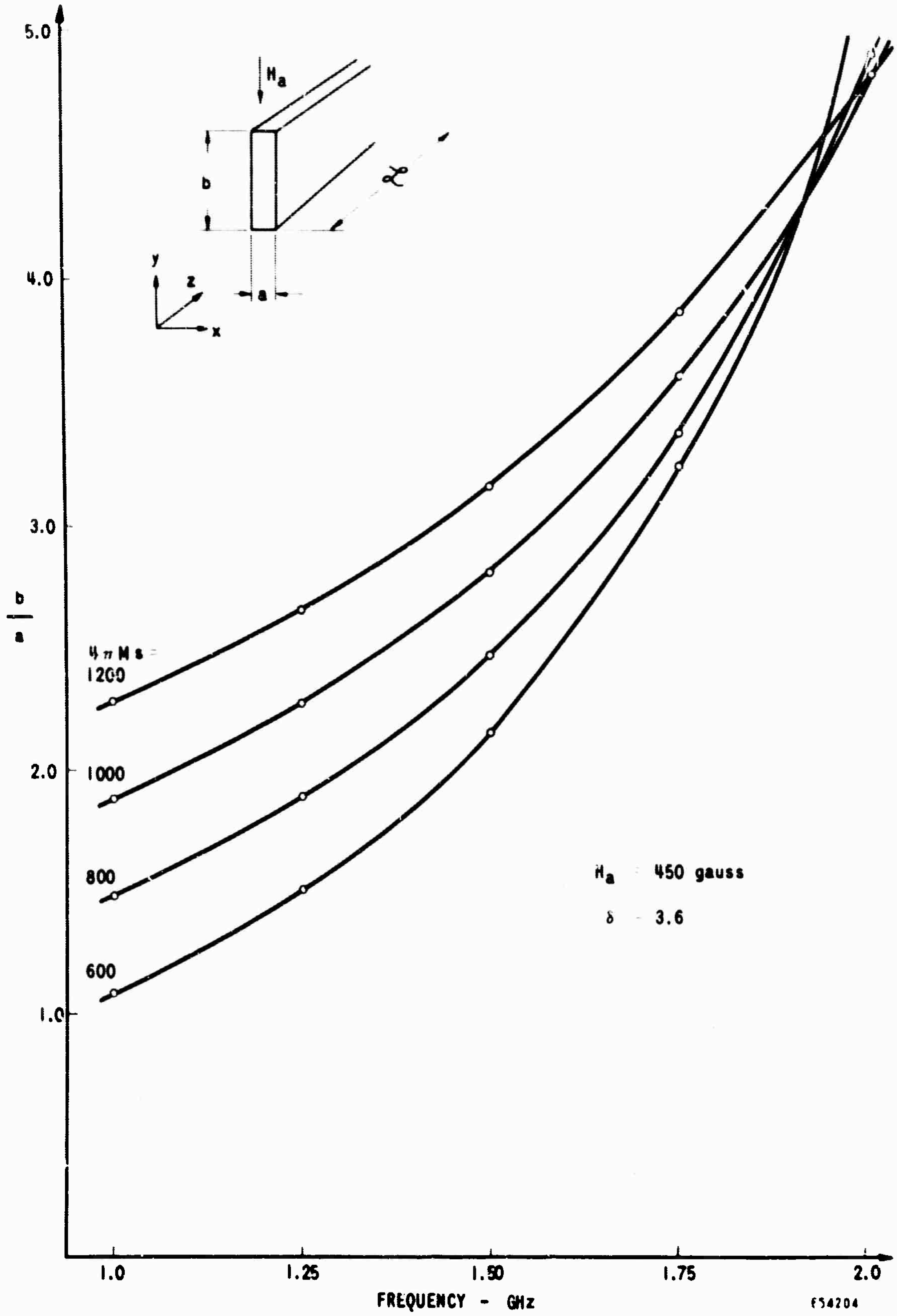


Figure 6-2 b/a vs Frequency - L-Band

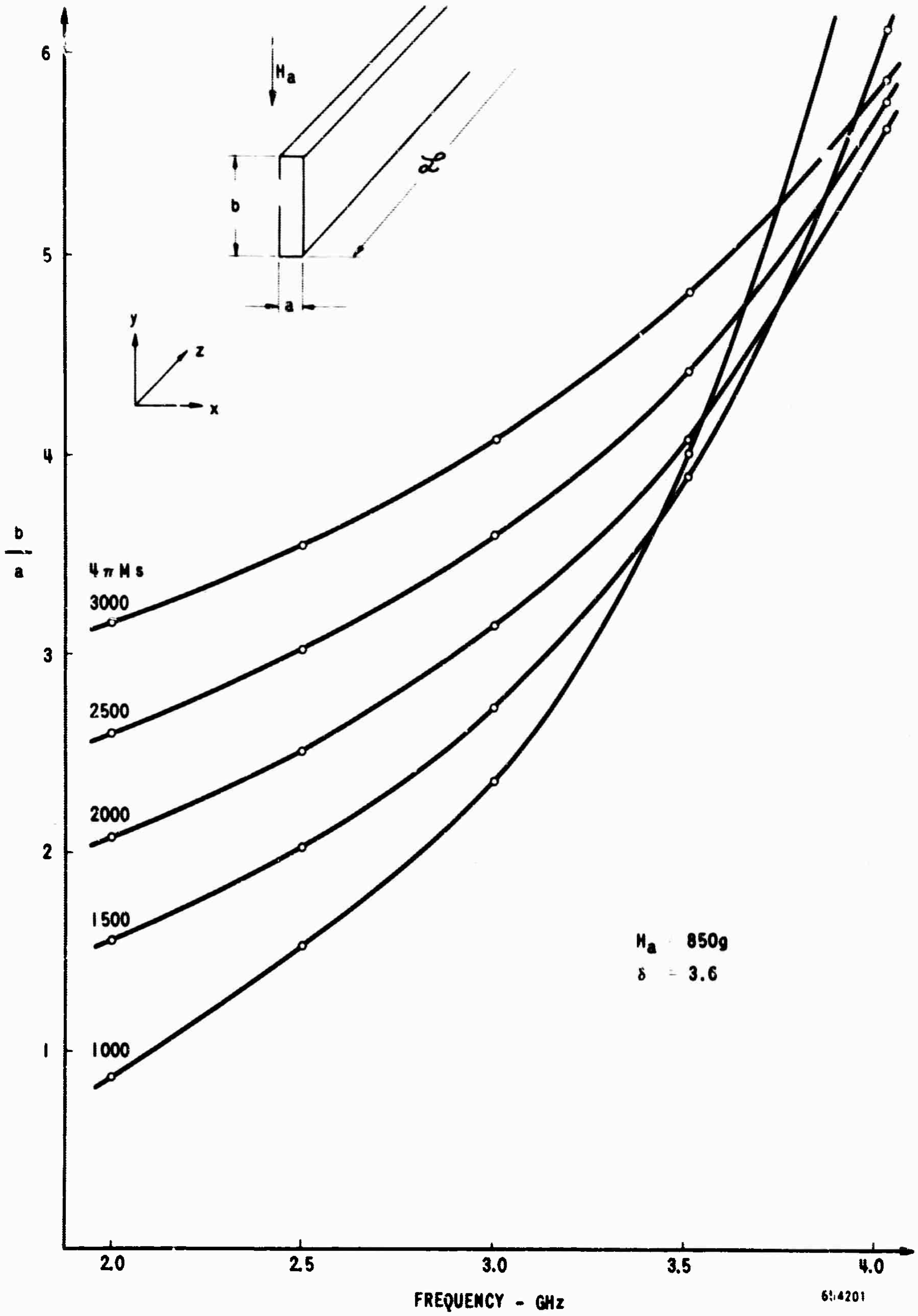


Figure 6-3 b/a vs Frequency - S-Band

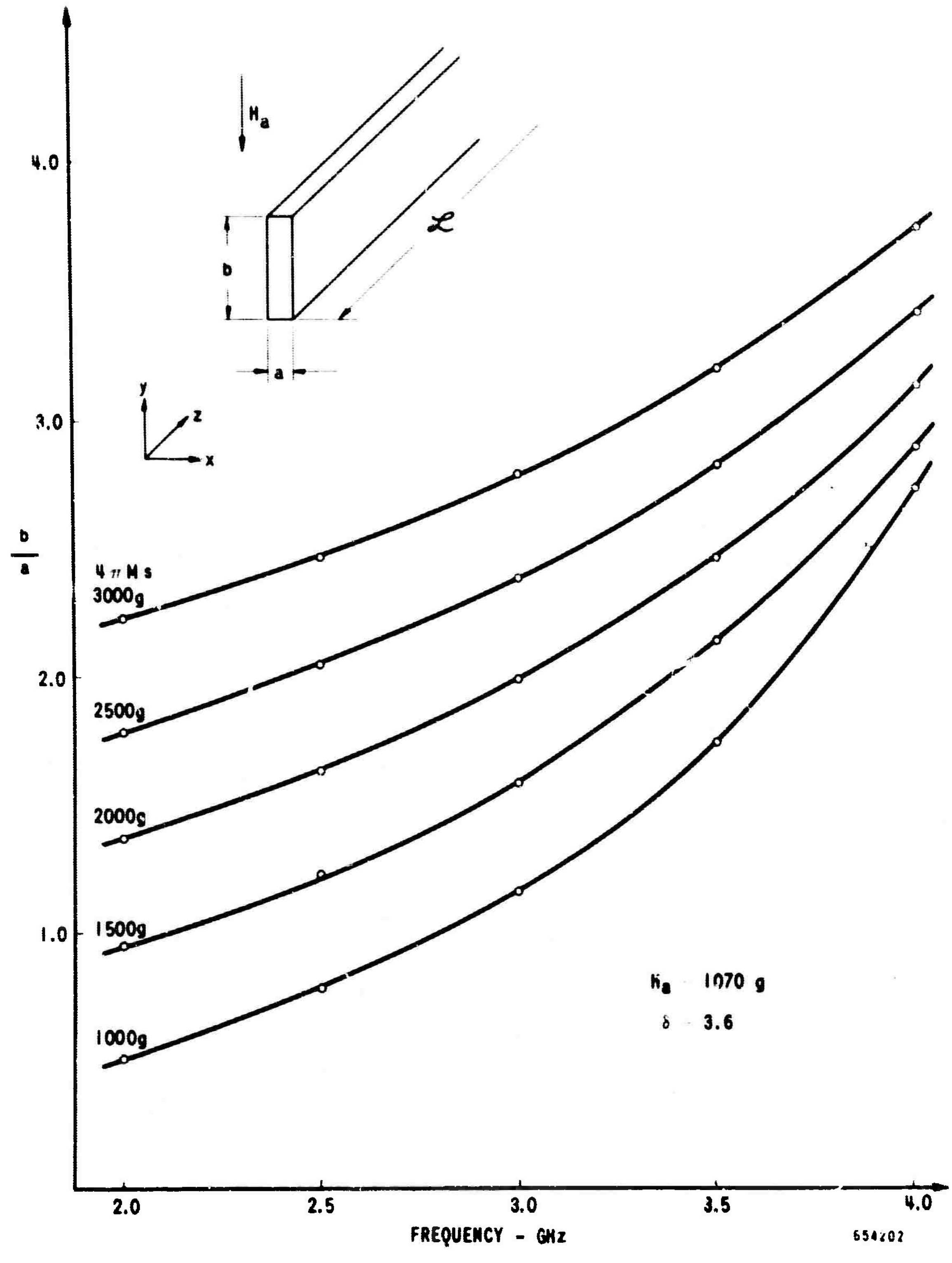


Figure 6-4 b/a vs Frequency - S-Band

7. MATERIAL PROPERTIES

Several materials were tested to check their characteristic properties and determine their suitability to be used in a CFA operating in either of L or S-bands.

These materials would be used in a single resonance device and as such would possess broad linewidth. As mentioned previously, they fall within two categories:

7.1 Substituted materials. These ferrite materials are all substituted nickel iron spinels. The substitution elements are aluminum cobalt, magnesium, copper, etc, depending on the particular ferrite chosen.

7.1.1 TT2-118. This material is fabricated by Transtech Inc. It is a nickel cobalt ferrite with aluminum oxide substitution of the iron oxide.

$4\pi M_s$	= 1797 g (SMDO) 1827 g (Research) at room temperature
ΔH at X-band	= 868 oersteds at room temperature
γ	= 3.69
ϵ'	= 8.95
$\tan \delta$	= 2.4×10^{-4}
μ''	= 1.616 (H = 0) 1.459 (H = 1000 g)

The Curie point is about 500°C, which would make it acceptable for use in a hot tube.

7.1.2 TT2-120. This ferrite is also fabricated by Transtech, Inc. It has the same substitution elements as TT2-118 but in different proportions.

It would also be a useful S-band material. Its measured properties are shown below.

$4\pi M_s$	= 1796 g (SMDO) 1905 g (Research) at room temperature
ΔH at X-band	= 917 oersteds at room temperature
γ	= 3.69
ϵ'	= 8.48
$\tan \delta$	= 2.5×10^{-4}
μ''	= 1.815 (H = 0) 1.624 (H = 1000 g)

The Curie temperature of the material is about 545°C.

7.1.3 Raytheon materials. Three experimental materials were made at Raytheon's Special Microwave Devices Operation ceramics facility. They are all nickel ferrite and designated by the symbols: NFA 253, NFCA 58 and NFT.

NFA 253 has aluminum oxide substituted for some iron. Its properties are:

$4\pi M_s$ = 592 g at room temperature
ΔH = 300 oersteds at X-band
γ = 5.3
T_c = 350°C

NFCA 58 is a nickel cobalt ferrite with aluminum substitution, its properties are:

$4\pi M_s$ = 1000 g at room temperature
ΔH = 673 oersteds at room temperature and at X-band
γ = 3.72
T_c = 400°C

NFT_1 is a nickel ferrite with titanium substitution. The measured properties are

$4\pi M_s$ = 1631 g at room temperature
ΔH = 742 g at room temperature and X-band
γ = 3.64

No further measurements were taken on these materials for the time being since similar ones are available commercially.

7.2 Porous materials. Two different porous materials were made and tested at Raytheon.

7.2.1 R164. This material was made at Special Microwave Devices Operation. It is a nickel ferrite with a density 75% that of X-Ray.

Its measured properties are shown below:

$4\pi M_s$ = 2300 g at room temperature
ΔH = 1213 oersteds at room temperature and X-band
γ = 3.77
ϵ' = 7.45
tan δ = 7×10^{-5}
μ'' = 1.657 (H = 0) 1.374 (H = 1000 g) at S-band.

This material can be used in a CFA at S-band.

7.2.2 MF10187-284. This is a magnesium manganese ferrite made at Research Division, heat treated to have a density 86% that of X-Ray.

Its measured properties are:

$4\pi M_s$	=	1063 g at room temperature
ΔH	=	770 oersteds at room temperature and X-band
γ	=	2.9
ϵ'	=	9.5
$\tan\delta$	=	$2.95\ 10^{-4}$
μ''	=	0.019 (H = 0) at C-band

Figure 7-1 shows the $4\pi M_S$ as a function of temperature. The curie temperature is about 400°C.

8. MATERIAL TESTS

Some ferrite materials were tested at microwave frequencies to determine loss and bandwidth at resonance.

The test vehicle was chosen to be a coaxial transmission line of 0.875 inch OD. To obtain resonance, it is necessary to create a region of circular polarization. This was done by half filling the coaxial line with alumina (ϵ' = 9). The matching to 50Ω is done with tapers.

It was decided to use a coaxial transmission line because it is the closest approach with available laboratory equipment, to the delay line used in the CFA.

A waveguide could have been the vehicle but there the field gradients are lower and their interaction with the ferrite material very weak.

Three materials were tested at L-band: R142, Sperry M40 and the porous MF 10187-284.

For each material, the ferrite slab size was calculated for a given field. The b dimenson of the ferrite slab is fixed at 0.200 inch since no bigger slab will fit our line.

a. R142 $4\pi M_S$ = 450 g γ = 2.0 Ha = 510 g

$\frac{b}{a}$ = 4.44 (0.200" x 0.045" x 6")

The field will be applied parallel to the 0.200 inch dimension.

b. Sperry M40 $4\pi M_s$ = 838 γ = 3.89 Ha = 453 g

$\frac{b}{a}$ = 2.22 (0.200" x 0.090" x 6.00")

The field will be applied parallel to the 0.200 inch dimension.

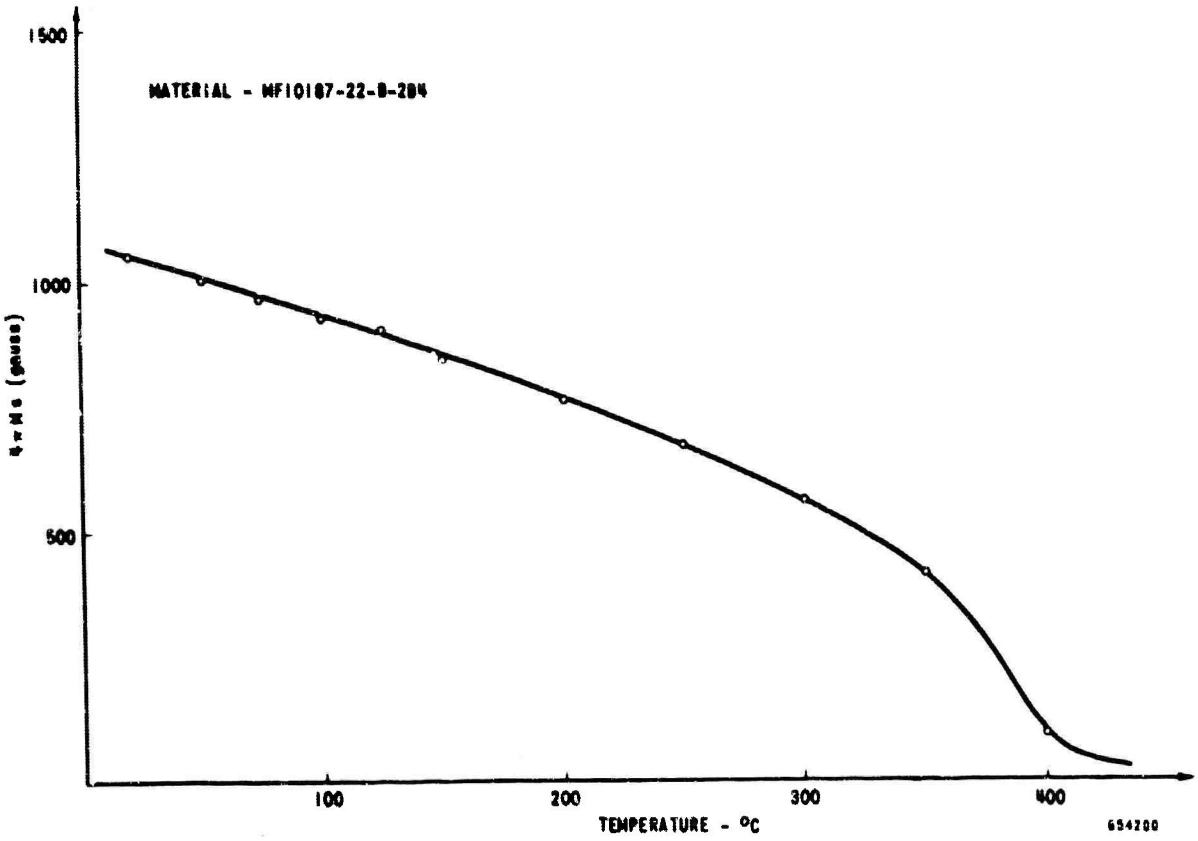


Figure 7-1 4 M_s vs Temperature

c. <u>MF10187-284</u> $4\pi M_s = 1063$ g $\gamma = 2.9$ Ha = 590 g

$\frac{b}{a} = 2.28$ (0.200" x 0.088" x 6.000")

The field is applied parallel to the 0.200 inch dimension.

The measured backward and forward losses are shown in Figures 8-1 and 8-2 respectively for the values of applied field shown.

The isolation curve obtained with R142 is the normal one to be expected and compares closely to what was measured with the CFA's delay line.

With the other two materials, it was impossible to obtain a clearly defined resonance. In addition, especially for material M40, the insertion loss was very high.

It can be explained from the fact that the material was not saturated and we are working in a region of low field loss.

The low field loss can exist if

$$\omega_o < \gamma\, 4\pi M_s \ .$$

In other words, to bias the ferrite in such a way that

$$H > 4\pi M_s$$

but

$$H = Hz - Ny \times 4\pi M_s \tag{8-1}$$

it is necessary to have the condition:

$$Ha > 4\pi M_s\,(1 + Ny) \tag{8-2}$$

For instance, with the Sperry material M40, it is necessary that Ha + 450 g for compatibility with the tube. This gives Ny = 0.304 for resonance condition, and, from

$$450 > 838\,(1 + 0.304)$$

which is obviously not satisfied.

$$510 > 450\,(1 + 0.183)$$
$$510 > 535$$

This is just at the limit of the low field loss.

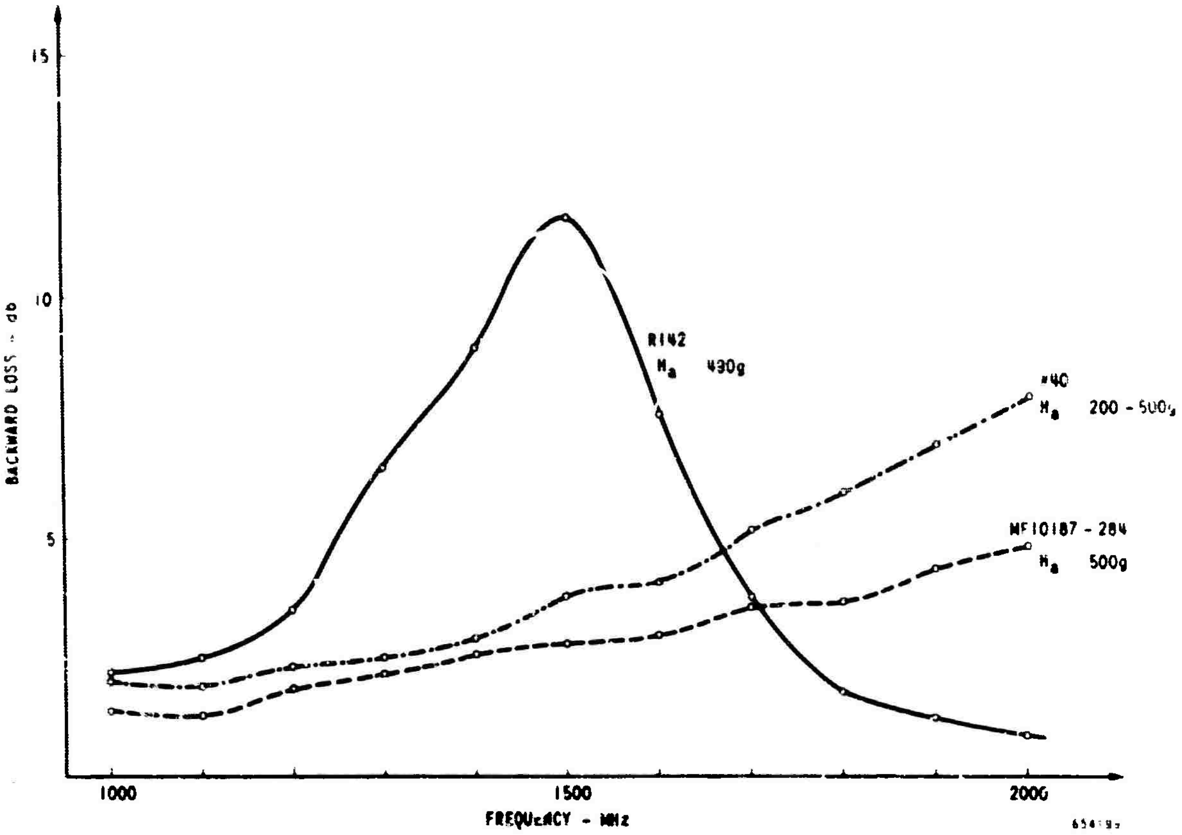


Figure 8-1 Backward Losses of Materials in Coaxial Transmission Line (L-Band)

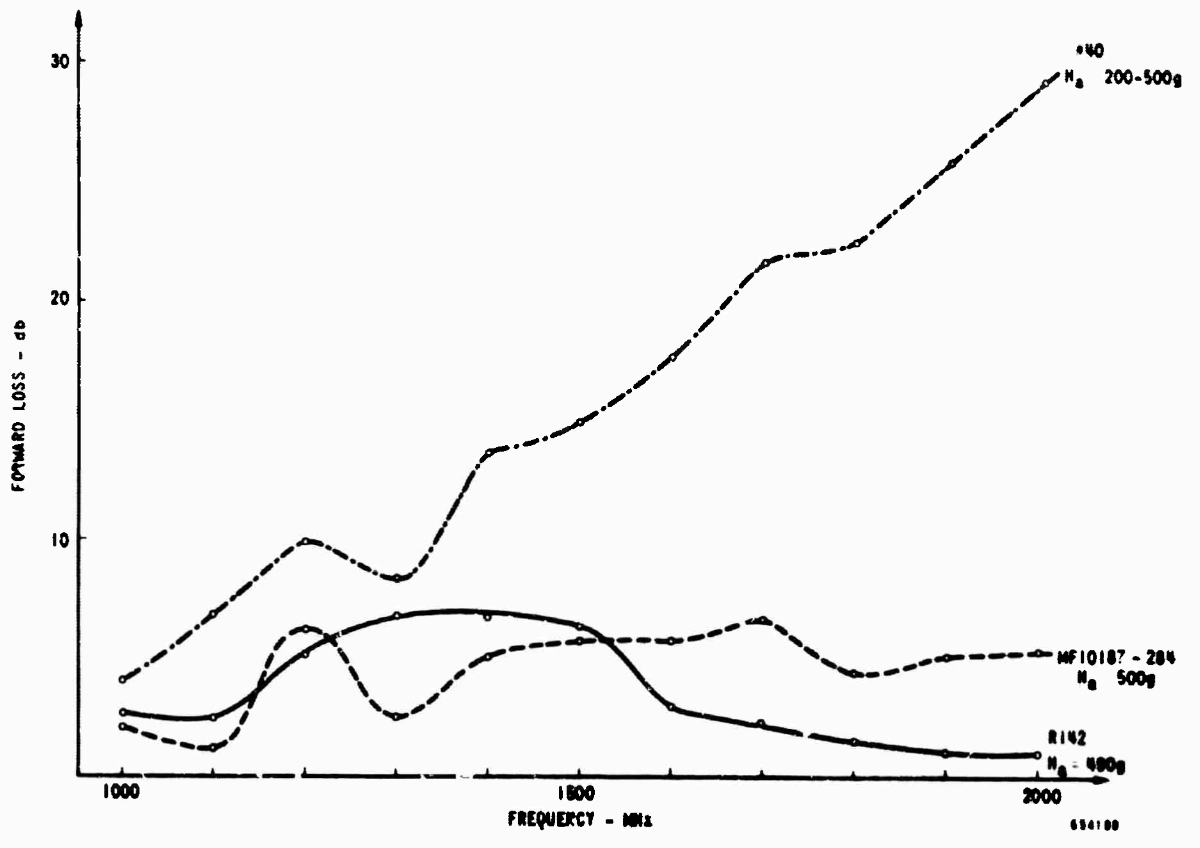


Figure 8-2 Forward Loss of Materials in Coaxial Transmission Line (L-Band)

Equation (8-2) introduces an additional limit which reduce further the choice of material to obtain resonance with the given applied field.

The curves of the reverse loss show that the attenuation increases with frequency, which seems to contradict the assumption of low field loss. But it may be due to the fact that while the low field loss per wavelength stays approximately constant the electric length increases with frequency.

<u>S-band tests.</u> Three materials were tested at S-band in the transmission line described in the previous paragraph.

One is a dense material made at Transtech, Inc. and called TT2-118; the other two are porous and made at Raytheon. They are R164 and MF10187-284. The slab size was calculated for each material assuming a nominal applied magnetic field Ha = 1070 g applied parallel to the broad face of the slab (0.200").

a. <u>R164</u> $4\pi M_s = 2300$ g $\gamma = 3.77$ Ha = 1070 g

$\frac{b}{a} = 2.12$ (0.200" x 0.094" x 6.000")

b. TT2-118 $4\pi M_s = 1789$ g $\gamma = 3.68$ Ha = 1070 g

$\frac{b}{a} = 1.77$ (0.200" x 0.113" x 6.000")

c. MF 10187-284 $4\pi M_s = 1063$ g $\gamma = 2.9$ Ha = 1070 g

$\frac{b}{a} = 2.16$ (0.200" x 0.093" x 6.000")

The measured backward and forward losses are shown in Figure 8-3 and 8-4 respectively.

Again the same phenomenon as described before are present.

If equation (8-2) is applied to each of the materials, then

for R164	$1070 > 2300 (1 + 0.680)$ $1070 > 3865$	not fulfilled
for TT2-118	$1070 > 1789 (1 + 639)$ $1070 > 2947$	not fulfilled
for MF10187-284	$1070 > 1063 (1 + 682)$ $1070 > 1788$	close to the limit

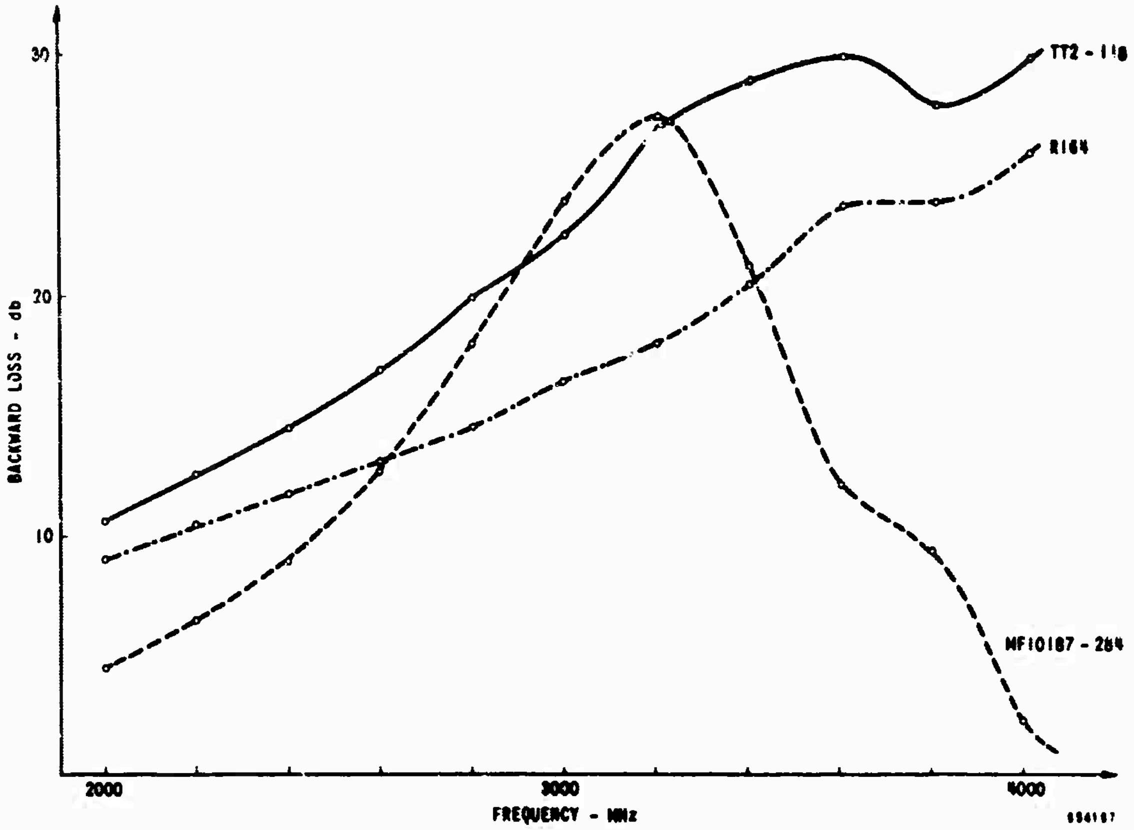


Figure 8-3 Backward Loss of Materials in Coaxial Transmission Line (S-Band)

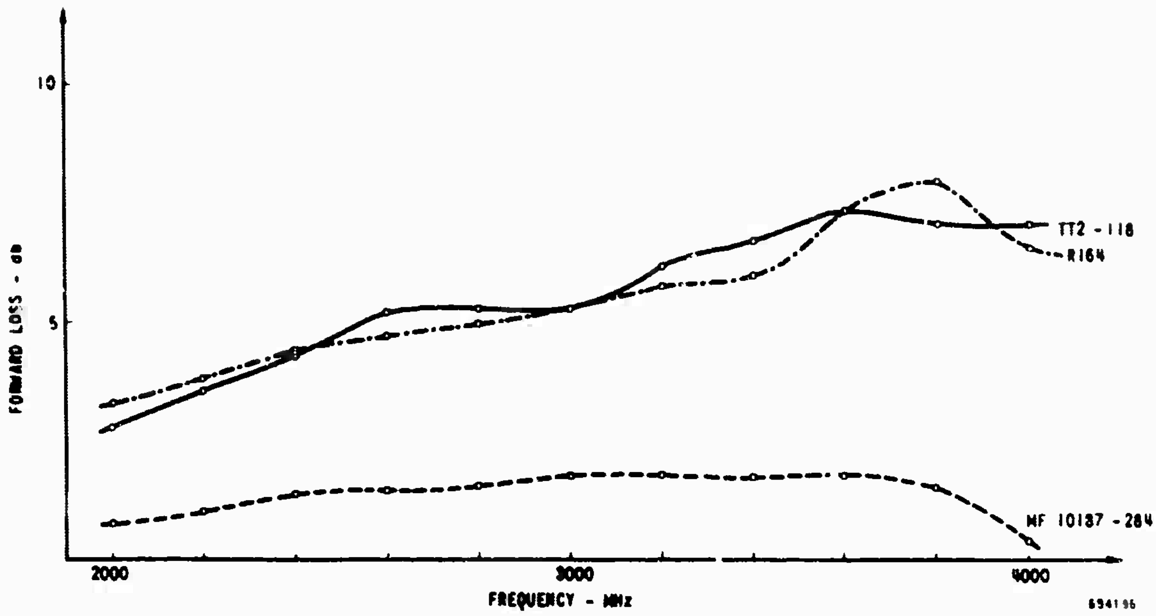


Figure 8-4 Forward Loss of Materials in Coaxial Transmission Line (S-Band)

At S-band, the porous magnesium manganese ferrite looks quite attractive, giving a figure of merit of 15.3. The backward loss is greater than 10 db from 2450 to 3750 MHz with a forward loss less than 1.8 db over the whole frequency range.

9. BONDING TECHNIQUES

9.1 Glass frits. It was shown in the previous report that bonding ferrite to ceramics with glass frits of the soda lime family was unsuccessful because the ferrite properties were affected by the glass.

This can be traced to the silica content of the glass used which, at high temperature, form with the ferrite some ferrosilicates which are extremely lossy at microwave frequencies.

One possible approach would be to use other compositions eliminating silican, such as phosphates. But since the hot pressing of ferrite on alumina seems successful as a bonding technique, the use of glass frits has been stopped for the time being.

9.2 Ferrite brazing to metals. A series of experiments was undertaken to study the effect of metallic brazing of the ferrite on to metal substrates.

The schedule of experiments was tailored to the actual brazing steps to which a crossed-field amplifier tube is subjected.

It was done as follows, using a porous nickel ferrite R164.

1. Sputter nickel in argon at an atmosphere of 10 - 20 μ maintaining the temperature below 200°C.

2. Electroplate nickel on top of sputtered surface.

3. Braze to copper with BT solder at 780°C in vacuum (sample 3-2)

4. Braze to copper in nitrogen.

   a. with silfos solder at 705°C (sample 4-1)

   b. with BT solder at 780°C (sample 4-2)

5. Braze to molybdenum with copper solder at 1100°C in nitrogen (sample 5-2)

6. Bond one of the sample 5-2 to copper using BT solder at 780°C in dissociated ammonia (reducing atmosphere) (sample 6-2)

In general, none of the experiments were successful, the ferrite properties being greatly affected. In one case, sample 6-2, the ferrite chip was actually reduced into metal'.

The measurement results are shown in Table 9.1.

TABLE 9.1

Sample No.	$4\pi M_s$ gauss	ΔH oersteds (X-band)	Remarks
1	2300	1213	Reference. R164 batch 451.
3-2	2215	-	linewidth too broad to be measured - bond broke by thermal shock
4-1	2274	-	linewidth too broad. sputtered film oxided.
4-2	2230	-	linewidth too broad good bond ferrite discolored.
5-2	-	-	ferrite crumbled, no sample could be obtained.
6-2	-	-	sample shrink, turned into metal!

The new program previously described should permit the discovery of what are the temperatures and atmospheres to which the ferrite material can be submitted without appreciable degradation.

10. HOT PRESSING TECHNIQUES

Bonding of ferrites to ceramic substrates by a hot-pressing technique has been moderately successful. Cracking of the ferrite on cooling from the hot-pressing temperature has been the major problem encountered. It is assumed to be caused by differences in physical properties of the ceramic and ferrite, the thermal expansion difference being the most important. Stresses created during cooling can exceed the ultimate strength of ferrite resulting in failure. Fortunately, the cracks are normal to the ferrite-ceramic interface and the ferrite remains firmly bonded to the ceramic. However, in the long-run, it will be essential to eliminate, or at least reduce the magnitude of this cracking. It can be anticipated that the more complex shapes to be hot-pressed will present greater problems in this regard than the flat, disc shaped samples currently being fabricated.

Several different alumina ceramics were selected initially, with the objective of choosing one with a thermal expansion matched as closely as possible to that of the ferrite. The aluminas are commercially available from the McDanel Corporation and consist of the following:

1) 99% pure Al_2O_3, 98% of theoretical density,
2) 99% pure Al_2O_3, 90% of theoretical density,
3) ~95% pure Al_2O_3, ~98% of theoretical density.

Thermal expansion data for the three ceramics are compared with three typical hot-pressed ferrites in Figure 10-1; expansion coefficients (the slopes of these curves) reveal a mismatch of about 25% in the best case which is somewhat greater than desired.

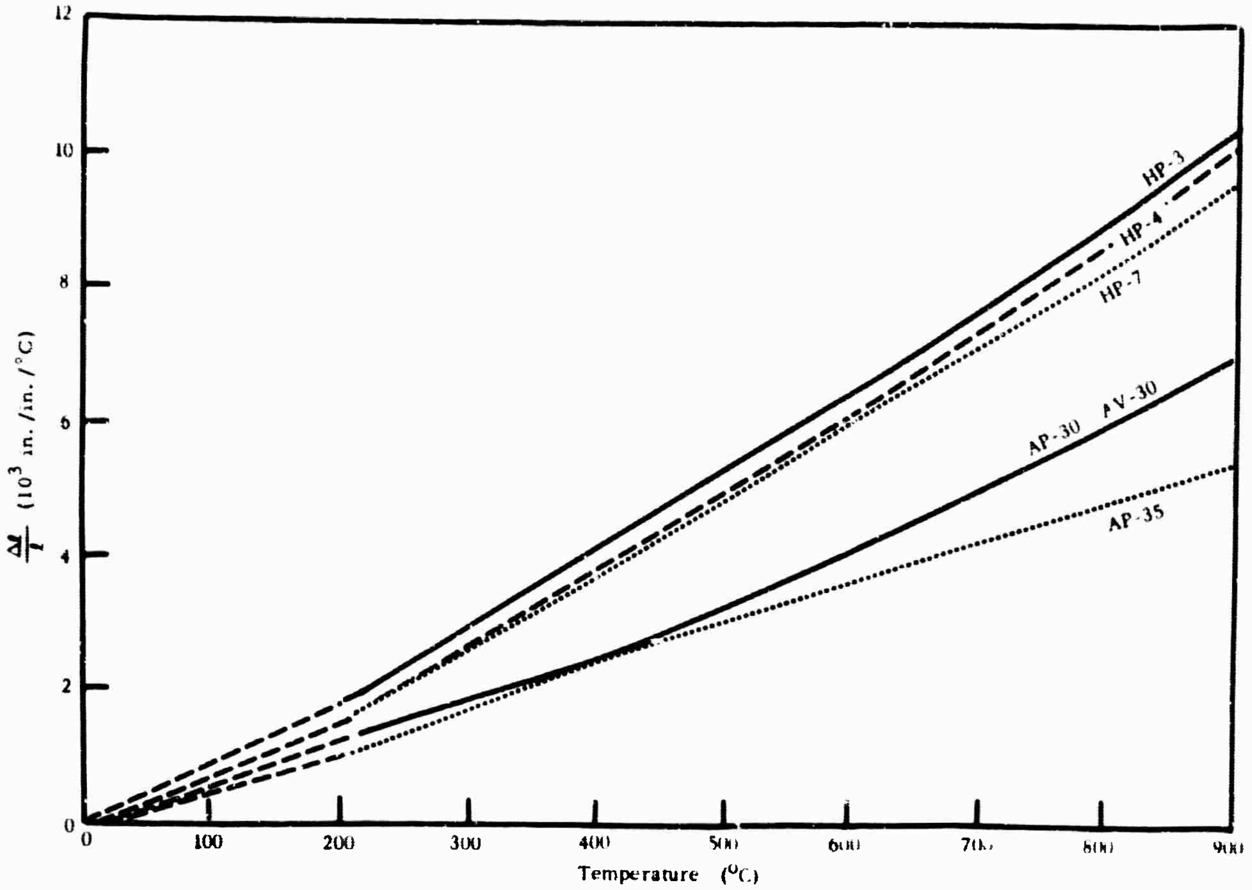


Figure 10-1 Expansion Curves for Three Aluminas and Three Hot Pressed Ferrites

A number of hot-pressing runs have been made, and best results were obtained at temperatures in the vicinity of 1100°C at pressures between 4000-5000 psi. Variations in the ratio of ferrite thickness to ceramic thickness indicates that at about 1:4 the best results are obtained. Typical cross sections are illustrated in Figure 10-2 for the extremes in this ratio. Of particular significance is the more extensive horizontal cracking in the thicker ferrite sample. This could lead to serious spalling during temperature cycling, either in the brazing and bakeout steps or in actual use in a completed tube. Although not entirely evident in this photograph, there is little cracking of this type in the 1:4 ratio composite; most of the cracking is normal to the bonded interface.

When the thermal expansion is matched identically, cracking does not occur. Hot-pressing a ferrite powder onto a ferrite presintered disk of the same composition and identical physical properties illustrates this point as shown in Figure 10-3. It is clear that with better property matching, hot-pressing the ferrite-ceramic composite will be more successful.

Attempts have been made to hot-press semicircular ferrite-ceramic shapes; preliminary results indicate that this will require a very extensive effort to be successful. An alternate approach consists of hot-pressing a number of flat, straight ferrite-ceramic bars, which will be subsequently cut and fitted to the desired radius of curvature.

Further work on this program will consist of:

1) Investigation of several other ferrites for bonding in an attempt to minimize or eliminate cracking and optimize microwave properties. The major effort thus far has been concentrated exclusively on the bonding problem and the ferrite microwave properties as influenced by variations in the hot-pressing procedure have not received as much attention; this area will be investigated in considerable detail.

2) Attempts to fabricate ferrite-ceramic ring structures will be intensified, with particular emphasis placed on larger sizes.

3) Ferrite materials will be subjected to the brazing and bake-out procedure to determine the effect on microwave properties, particularly dielectric loss.

11. CONCLUSIONS

1) The use of ferrites can be beneficial in the control of fast wave propagation in CFA's.

2) More effort is required before ferrites can be deployed as frequency selective attenuators in Amplitron tubes. This effort is secondary to the primary goals of the program.

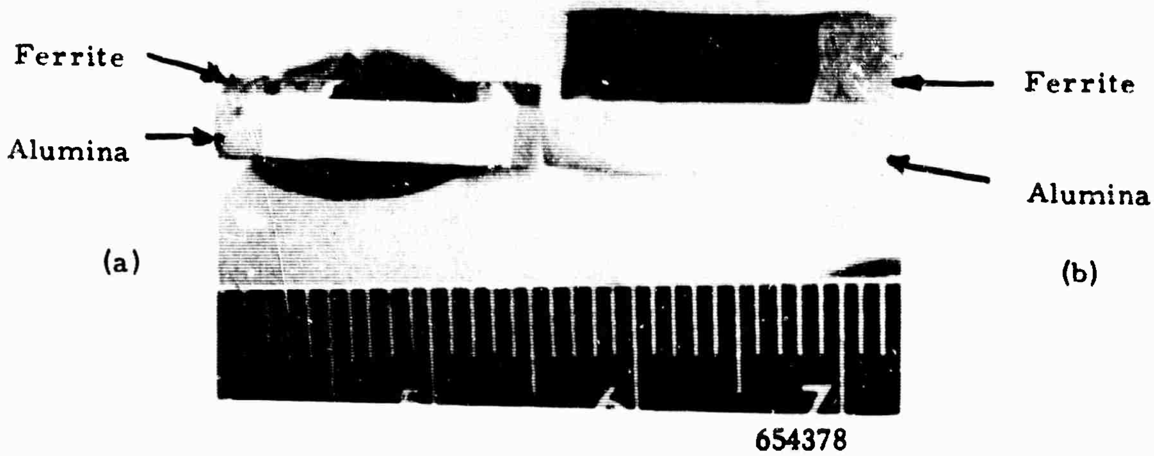


Figure 10-2 Section Through Hot-Pressed Ferrite-Alumina Composites With Thickness Ratios of a) 1:4 and b) 1:1

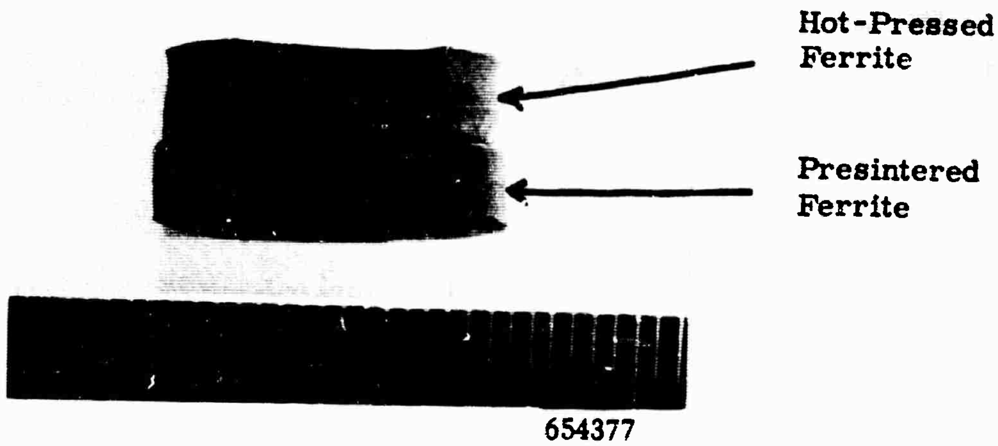


Figure 10-3 Section Through a Hot-Pressed Ferrite on a Presintered Disk of the Same Composition

3) A potentially serious problem area has been encountered in high temperature brazing of ferrites. More study and experiment is required.

4) The results of both theoretical and experimental studies of broadbanding have been quite encouraging thus far. In particular, desirable properties have been demonstrated over half an octave in S-band with a porous manganese ferrite, MF 10187-284.

5) Promising results have been obtained in the area of ferrite-ceramic bonding by means of hot pressing techniques.

12. PROGRAM PLANS - FIFTH QUARTER

Two main areas of investigation will be pursued during the forthcoming quarter.

1) The technology problems associated with bonding ferrites to ceramic will be investigated in depth. To this end the effects of firing temperatures and atmospheres will be determined for various materials and effort in the area of hot pressing will be continued.

2) Plans for the hot test vehicle will be formulated, i.e. basic questions as to how the ferrite can be mechanically assembled into a CFA will be studied. Following a decision in this matter cold testing of ferrites in the actual test vehicle will be done. Hot testing is not anticipated until the 6th quarter.

In addition to these two main fields of effort other areas of interest such as the Amplitron investigation will be continued if time and manpower permit.

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13. ABSTRACT The objective of this program is to develop the knowledge and technology necessary to take full advantage of the unidirectional attenuative properties of ferrites in achieving improved gain and bandwidth in crossed-field microwave amplifiers and oscillators.

During this fourth quarterly period, activities included further cold testing of ferrite materials in the L-band cold test vehicle and in the S-band QKS1267 Amplitron. A number of brazing experiments were carried out, and considerable effort was expended in the study of hot pressing techniques for the bonding of ferrites to alumina. The results were promising.

The results of both theoretical and experimental studies of broadbanding have been encouraging. In particular, desirable properties have been demonstrated over half an octave in S-band with a porous manganese ferrite.

The results of the first year's work suggest that good rf performance is fairly easy to achieve but that the demonstration of these properties in an actual CFA must await solution of the technological problems of bonding and exposure of the ferrites the brazing conditions. The major aim of the second year will be the realization of hot tests at the earliest possible time.

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Crossed Field Amplifiers						
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